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Virtual Flight Navier-Stokes Solver and its Application

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Abstract

A multi-purpose CFD software VFNS (Virtual Flight Navier-Stokes solver) is developed for aerodynamic and flight dynamic applications. The software is specifically designed to support the research works on coupling problems between aerodynamics and flight dynamics. It employs 6-DOF capability for simulating forced or free moving problems and chimera capability for simulating moving body dynamics including control laws. These challenging applications are enabled by coupling an unsteady, parallel Navier-Stokes flow solver with flight dynamics in sub-iterations of dual-time stepping algorithm. This paper will introduce the numeric methods used in this software and give some applications in free-to-pitch simulations for a square cross-section missile.

Keywords: VFNS; Aerodynamics; Flight Mechanics; Chimera Technology; Adams Prediction-Correction

1. IntroductionMain text

Conventional flight simulations are based on aerodynamic models using data obtained from experiment and CFD. The flight simulation therefore depends to a large extent on the quality of the aerodynamic model. It is also challenged by the rapid maneuverability which incorporates significant hysteresis which will not be described by stability derivatives based on linear aerodynamic models.

Another new flight simulation method is to solve the unsteady RANS and 6-DOF equations together with prescribed active or passive controls[1]. URANS is not only capable to produce the aerodynamic forces, but also to capture the nonlinear hysteresis effects. Through coupling with CFM (Computational

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Flight Mechanics), the CFD based simulation is potential to obtain more reliable dynamic results, though it is not likely to run flight simulations for routine studies.

The main objective of this paper is to present a CFD based flight simulation software VFNS, shortened from Virtual Flight Navier-Stokes solver. This paper briefly introduces the CFD method, the coupling method between aerodynamics and flight mechanics as well as the moving body method. To validate the new software, several missile longitudinal motions with fin deflections have been done and are presented.

2. Virtual Flight Navier-Stokes Slover

2.1. Flow Solver

The flow solver uses a cell centered finite volume technique to solve the Unsteady Reynolds Averaged Navier-Stokes (URANS) equations. The convective and pressure terms are differenced using either the Roe's upwind flux-difference-splitting technique or the Van Leer's flux-vector-splitting technique. The MUSCL approach of van Leer is used to compute state-variable interpolations at the cell interfaces. The shear stress and heat transfer terms are centrally differenced. The solver is advanced in time with pseudo time sub-iteration, or dual-time stepping[2]. By using dual-time stepping technology, the time step could be larger while keep a rather good stability and precision. Another advantage is that it enables a tight coupling between CFD and CFM which will be introduced later. S-A is chosen to simulate the turbulence flow.

2.2. Solving Flight Equations

The 6-DOF equations are defined as

$$
\begin{aligned}
&\frac{dv_{\mathrm{x}}}{dt} = F_{\mathrm{x}}^{\mathrm{i}}/m = \left(F_{\mathrm{xa}}^{\mathrm{i}} + F_{\mathrm{xe}}^{\mathrm{i}} + F_{\mathrm{xg}}^{\mathrm{i}}\right)/m &&\frac{d\omega_{\mathrm{x}}^{\mathrm{b}}}{dt} = \left[M_{\mathrm{x}}^{\mathrm{b}} + \left(I_{\mathrm{yy}}^{\mathrm{b}} - I_{\mathrm{zz}}^{\mathrm{b}}\right)\omega_{\mathrm{y}}^{\mathrm{b}}\omega_{\mathrm{z}}^{\mathrm{b}}\right]/I_{\mathrm{xx}}^{\mathrm{b}}\\
&\frac{dv_{\mathrm{y}}}{dt} = F_{\mathrm{y}}^{\mathrm{i}}/m = \left(F_{\mathrm{ya}}^{\mathrm{i}} + F_{\mathrm{ye}}^{\mathrm{i}} + F_{\mathrm{yg}}^{\mathrm{i}}\right)/m &&\frac{d\omega_{\mathrm{y}}^{\mathrm{b}}}{dt} = \left[M_{\mathrm{y}}^{\mathrm{b}} + \left(I_{\mathrm{zz}}^{\mathrm{b}} - I_{\mathrm{xx}}^{\mathrm{b}}\right)\omega_{\mathrm{z}}^{\mathrm{b}}\omega_{\mathrm{x}}^{\mathrm{b}}\right]/I_{\mathrm{yy}}^{\mathrm{b}}\\
&\frac{dv_{\mathrm{z}}}{dt} = F_{\mathrm{z}}^{\mathrm{i}}/m = \left(F_{\mathrm{za}}^{\mathrm{i}} + F_{\mathrm{ze}}^{\mathrm{i}} + F_{\mathrm{zg}}^{\mathrm{i}}\right)/m &&\frac{d\omega_{\mathrm{z}}^{\mathrm{b}}}{dt} = \left[M_{\mathrm{z}}^{\mathrm{b}} + \left(I_{\mathrm{xx}}^{\mathrm{b}} - I_{\mathrm{yy}}^{\mathrm{b}}\right)\omega_{\mathrm{x}}^{\mathrm{b}}\omega_{\mathrm{y}}^{\mathrm{b}}\right]/I_{\mathrm{zz}}^{\mathrm{b}}\\
&\frac{dx}{dt} = v_{\mathrm{x}} &&\frac{d\vartheta}{dt} = \omega_y^b \sin\gamma + \omega_{\mathrm{z}}^{\mathrm{b}}\cos\gamma\\
&\frac{dy}{dt} = v_{\mathrm{y}} &&\frac{d\psi}{dt} = (\omega_y^b \cos\gamma - \omega_{\mathrm{z}}^{\mathrm{b}}\sin\gamma)/\cos\vartheta\\
&\frac{dz}{dt} = v_{\mathrm{z}} &&\frac{d\gamma}{dt} = \omega_x^b - (\omega_y^b \cos\gamma - \omega_{\mathrm{z}}^{\mathrm{b}}\sin\gamma)\tan\vartheta
\end{aligned}
\tag{1}
$$

Here, the subscript "a" indicates aero forces, "e" indicates outside forces and "g" indicates gravity. The superscript "b" indicates the components in body reference frame. ϑ, ψ and γ are the three Euler angles.

Above nonlinear equations should be solved by numeric methods and be coupled with CFD computations. The coupling computational method is a key factor to affect the simulation results. For CFD computations, the time step should not be too large to cause divergence. However, for virtual flight simulations, the simulation time is very long due to the long physical time (several seconds or even more). Furthermore, small time step should be used to reduce the cumulation errors of CFM. Therefore, it is a key issue to use a coupling method which could use large time step while ensures the CFD computation convergent and has the same precision level of CFM.

The Adams prediction-correction method is chosen to solve the flight equations and couple the CFM and CFD in sub-iterations of dual-time stepping. After time step n is completed and aero forces are produced by CFD computation, the 6-DOF state variables at time step n+1 will be predicted first using Adams-Bashforth prediction method with first to third order accuracy in time. These prediction results will be used to place the body to a new position and attitude. Then the CFD computation will be advanced using dual-time stepping technology. In each sub-iteration during the dual-time step, the CFD produces new aero forces and thus the 6-DOF state variables should be corrected. At this stage, Adams-Moulton correction method with first to third order accuracy in time will be applied. After all the sub-iterations are completed or the state variables are converged, computation will be advanced to next time step n+2.

The Adams-Bashforth prediction schemes are

$$x_{n+1} = x_n + \Delta t f(x_n, t_n) \tag{2}$$

$$x_{n+1} = x_n + \Delta t \left[\frac{3}{2} f(x_n, t_n) - \frac{1}{2} f(x_{n-1}, t_{n-1}) \right] \tag{3}$$

$$x_{n+1} = x_n + \Delta t \left[\frac{23}{12} f(x_n, t_n) - \frac{16}{12} f(x_{n-1}, t_{n-1}) + \frac{5}{12} f(x_{n-2}, t_{n-2}) \right] \tag{4}$$

And the Adams-Moulton correction schemes are

$$x_{n+1} = x_n + \Delta t f(x_n, t_n) \tag{5}$$

$$x_{n+1} = x_n + \Delta t \left[\frac{1}{2} f(x_{n+1}, t_{n+1}) + \frac{1}{2} f(x_n, t_n) \right] \tag{6}$$

$$x_{n+1} = x_n + \Delta t \left[\frac{5}{12} f(x_{n+1}, t_{n+1}) + \frac{8}{12} f(x_n, t_n) - \frac{1}{12} f(x_{n-1}, t_{n-1}) \right] \tag{7}$$

2.3. Moving Body Problems

Overset gird (chimera method) is used to simulate multi-body moving problems, especially for fin deflection. The current version of VFNS uses user-defined mesh faces as the initial hole boundaries. This is not an intelligent hole-construction method and may result in a poor interpolation stencils. To improve the precision, a method similar to Wey's advancing front technique[3] is used. In VFNS, interpolations should be found for outer interpolation boundaries first. Then these points' donor cells are marked to a number greater than 1 which indicates that it should not be cut off in the following hole-construction step. The inverse map method[4] is used to find donor cells and stencil interpolations.

2.4. Software Design and Integration

VFNS is designed to simulate many motion types. The following typical motions can be implemented by VFNS:

1. multi-DOF forced motion.

2. multi-DOF free motion.
3. multi-DOF forced and free motion, for example, free to roll in fast pitch-up motion.
4. body relative motion.

Taking the advantages of multi-motion types and parallel computations, VFNS has been successfully used to simulate some complex flow problems such as free-to-roll simulations of a complex missile configuration at angle of attack from 15° to 40°. These successful applications motivate us to further the virtual flight research introducing control laws. The following section will introduce some functional test works in longitudinal simulation with fin deflection.

3. Longitudinal Simulation

A square missile[5] with "+" configuration is chosen to run longitudinal simulation. Fig.1 shows the missile configuration and chimera gird which has about 3 millions of cell points. All computations were conducted at Mach=0.6 and $Re=15.7\times10^6$/m.

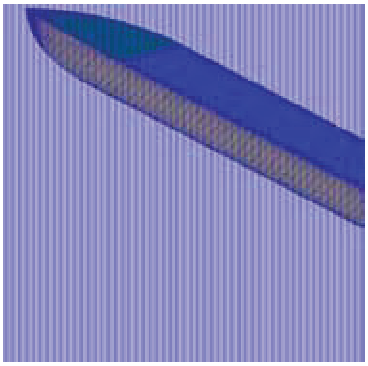

Fig.1 Square Missile Configuration and Chimera Grid

3.1. Static Computations

The force results are shown in Fig.1 for normal force coefficient CN, axial force coefficient CA and pitching moment coefficient Cm. Chimera results are compared with results of conventional 1-1 blocking gird as marked with triangles. The two groups of force results agree very well.

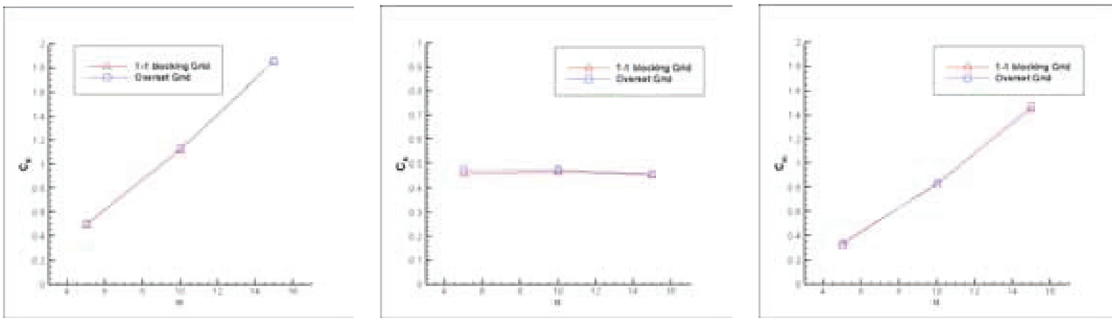

Fig.2 Static Force Coefficient Results

3.2. Longitudinal Simulation

Simulations were conducted at mach number 0.6 and the time step is 0.005s. The two horizontal fins are deflected following the law as:

$$\begin{cases} \delta_e = -1 - \sin(10\pi t - \pi/2) & t \le 0.1\text{s} \\ \delta_e = -2 & t > 0.1\text{s} \end{cases} \tag{8}$$

The second order adams prediction-correction method was used to solve the flight mechanic equations. Simulation results are shown in figure 2. Fig.2(a) shows the convergence history for the change of alpha in a time step. $d\alpha$ converged in a reasonable number of sub-iteration step. If the two horizontal fins were not deflected, the angle of attack would stagnate to 0°. Through introducing fin deflection angles, the final angle of attack stagnates to 16° after several oscillatory cycles in 3 seconds as shown in Fig.2(b). This shows the active control effect of the fins.

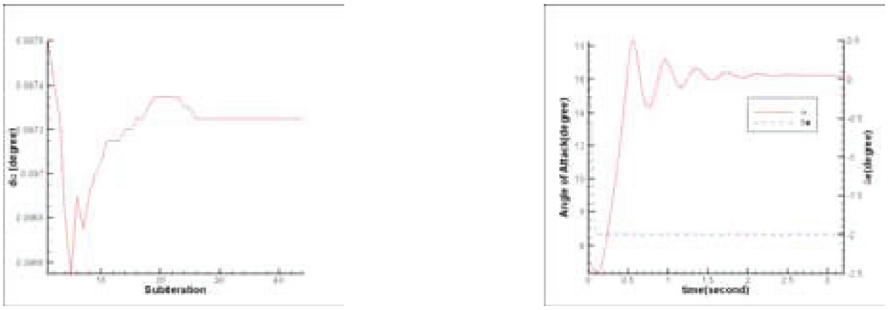

Fig.3. (a) Convergence of pitching angle for one time step; (b) Free to pitch motion – Angle of attack and elevator deflection angle

4. Summary

A multi-purpose CFD software VFNS was developed to simulate moving-body problems. At the core of the software is the use of finite volume flow solver with dual-time stepping technology, Adams prediction-correction coupling method and chimera technology. This software not only enables steady complex flow simulations for complex configurations, but also enables extensive moving-body simulations for relative motions as well as non-relative forced or free motions. Some simple functional tests on a square missile show its potentials in studying dynamic problems.

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